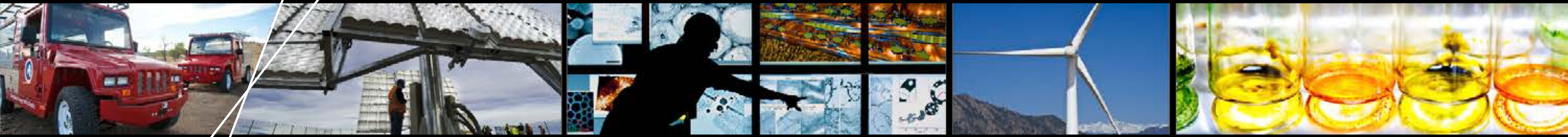
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

R&D Efforts for Enabling High Penetration Photovoltaics in U.S. Distributed Generation

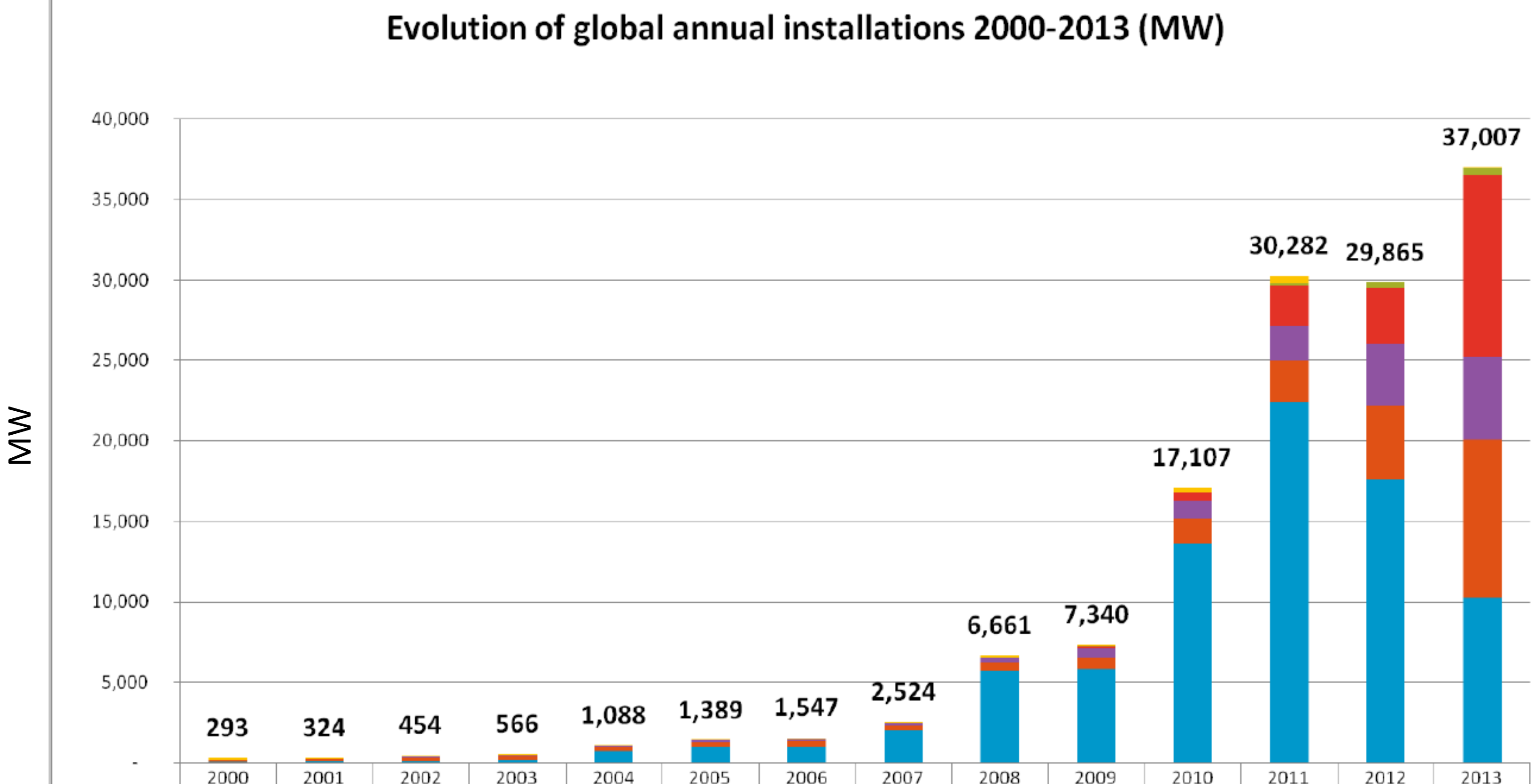


October 29, 2014

Dr. Dan E. Arvizu
Laboratory Director

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

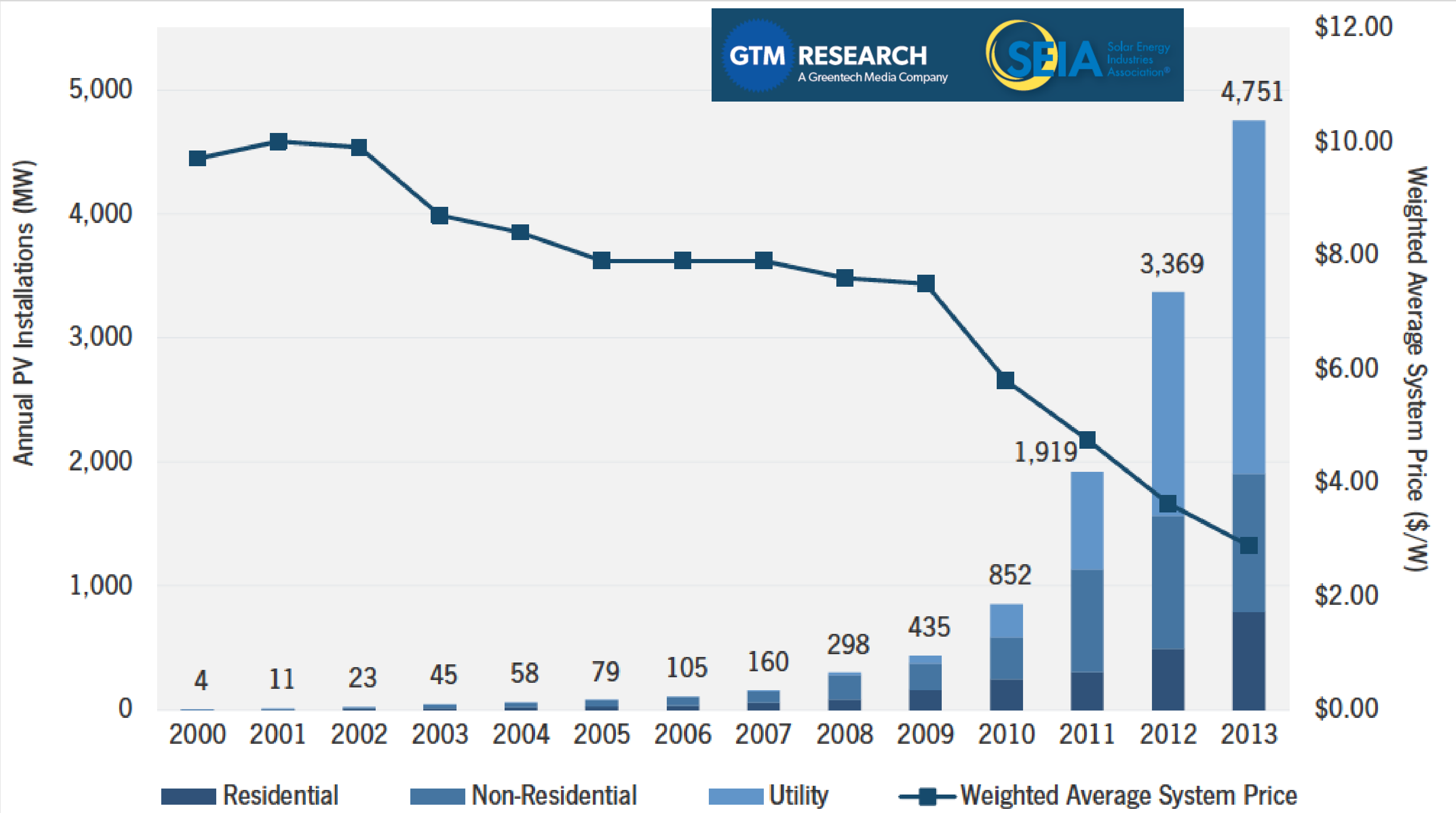
Global PV Market - Historic



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
ROW	88	56	80	77	29	10	105	42	76	80	284	508	-	85
MEA	-	-	-	-	1	0	0	1	1	22	46	125	365	383
China	19	5	19	10	10	8	10	20	40	160	500	2,500	3,500	11,300
AMERICA	2	3	30	48	61	82	110	166	306	500	1,082	2,181	3,774	5,153
APAC	126	128	190	230	282	304	325	271	530	745	1,578	2,562	4,646	9,833
Europe	58	133	134	202	705	985	997	2,023	5,708	5,833	13,616	22,407	17,580	10,253
TOTAL	293	324	454	566	1,088	1,389	1,547	2,524	6,661	7,340	17,107	30,282	29,865	37,007

Source: EPIA

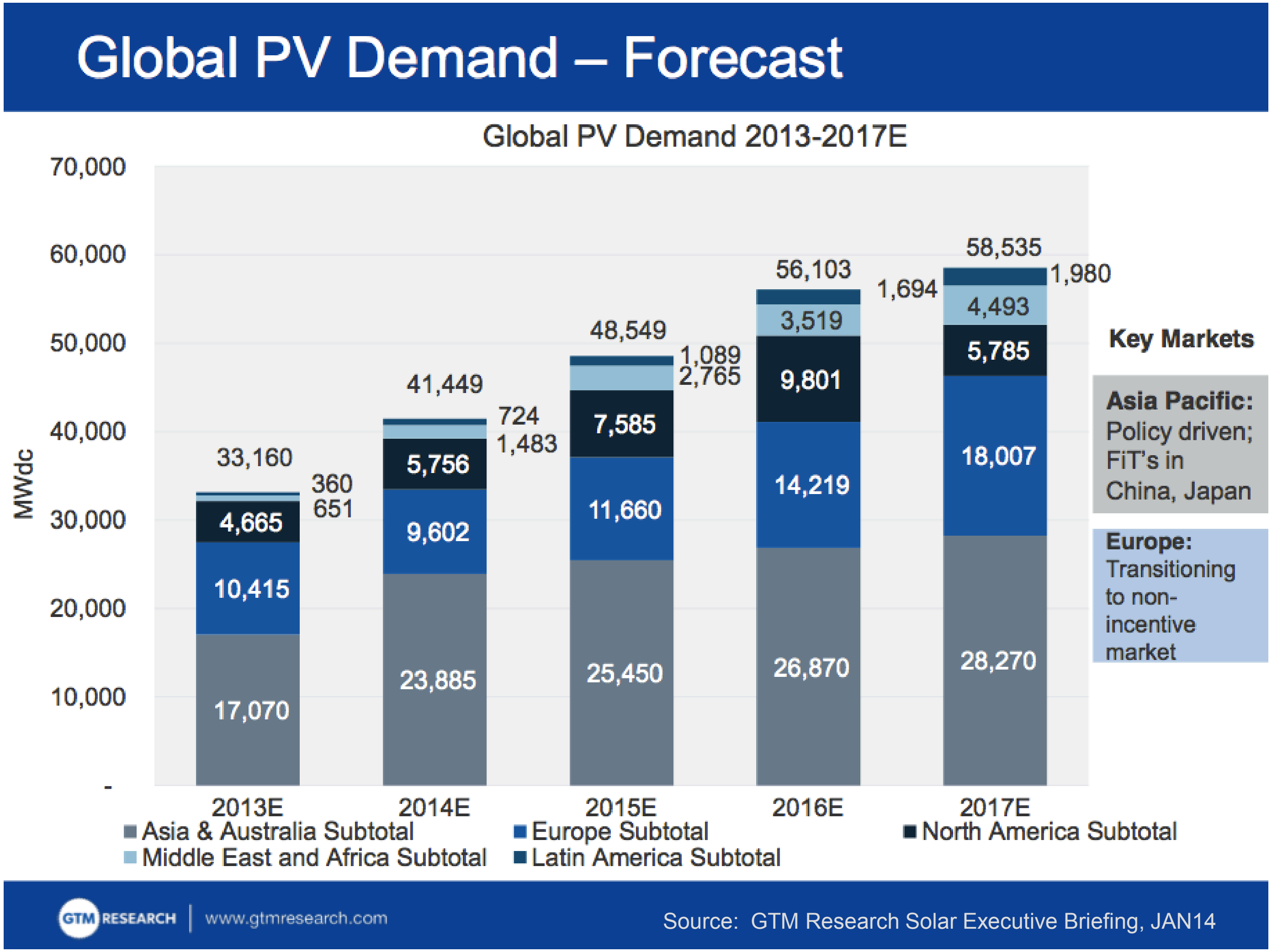
US PV Market - Historic



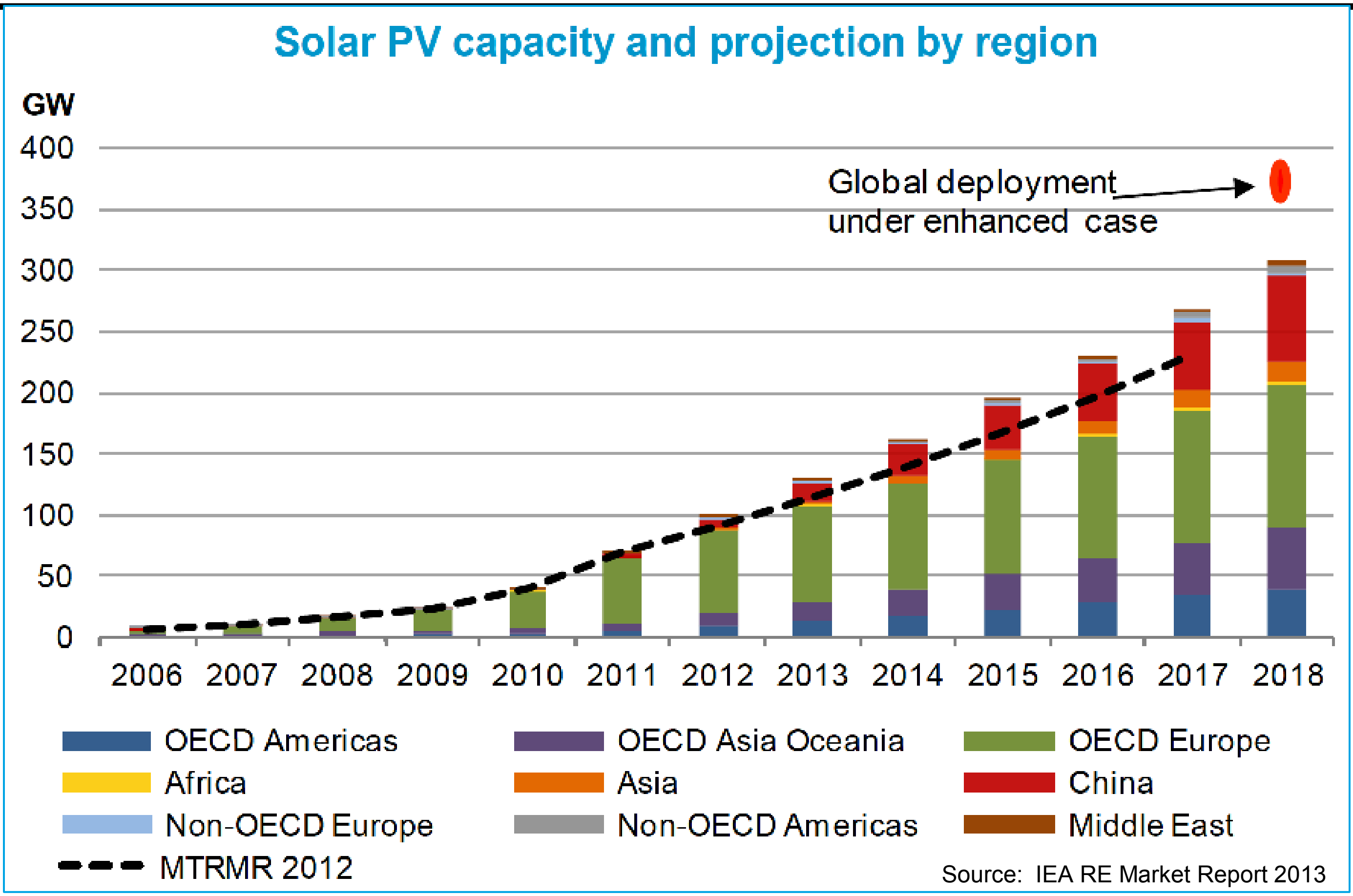
Installations (MW)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Residential	1	5	11	15	24	27	38	58	82	164	246	304	494	792
Non-Residential	2	3	9	27	32	51	67	93	200	213	339	831	1,072	1,112
Utility	0	3	2	3	2	1	0	9	16	58	267	784	1,803	2,847
Total	4	11	23	45	58	79	105	160	298	435	852	1,919	3,369	4,751

Sources: GTM Research/SEIA and Lawrence Berkeley National Laboratory

Global PV Demand Forecast



TW Scale: How Long?



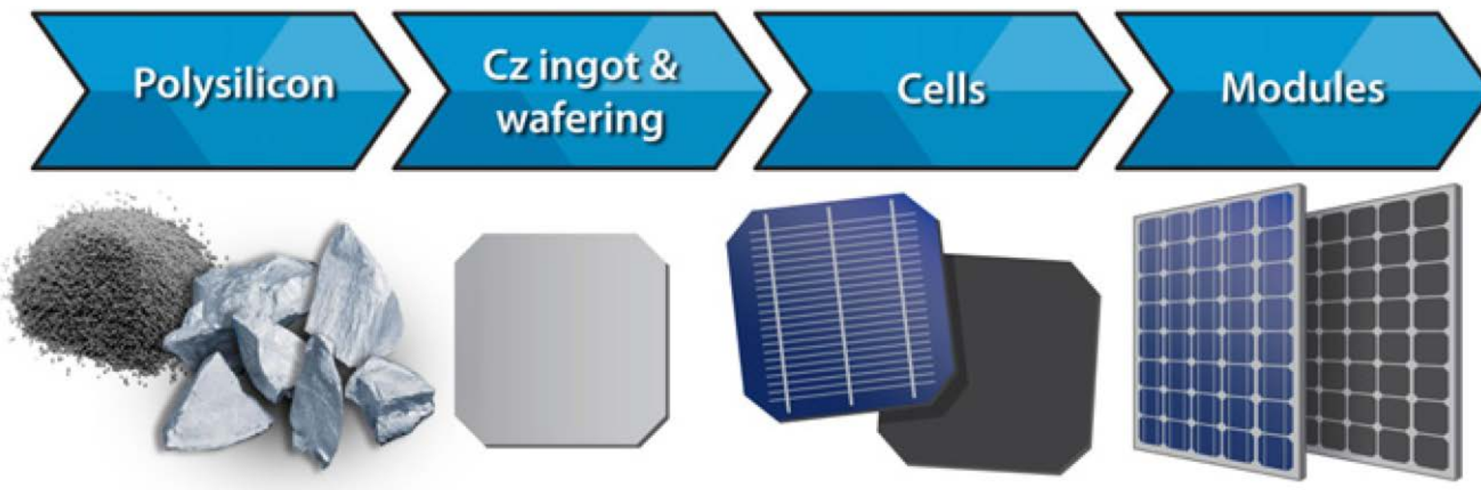
- **300GW by 2018, 1TW not before 2030.**
- **Much too slow given the current understanding of global climate change.**

IEA Forecast: Small Contribution in 2035

	Electrical capacity (GW) 2011	2020	2025	2030	2035	Shares (%) 2011	2035	CAAGR (%) 2011-2035
	New Policies Scenario					NPS	NPS	NPS
Total capacity	**5 456**	**7 308**	**8 121**	**8 922**	**9 760**	**100**	**100**	**2.5**
Coal	1 739	2 147	2 264	2 393	2 503	32	26	1.5
Oil	439	362	317	288	274	8	3	-1.9
Gas	1 414	1 854	2 058	2 247	2 462	26	25	2.3
Nuclear	391	471	512	545	578	7	6	1.6
Hydro	1 060	1 361	1 493	1 617	1 731	19	18	2.1
Bioenergy	93	154	190	226	266	2	3	4.5
Wind	238	612	797	960	1 130	4	12	6.7
Geothermal	11	19	27	35	43	0	0	5.9
Solar PV	69	312	437	564	690	1	7	10.1
CSP	2	14	23	40	70	0	1	16.7
Marine	1	1	3	6	14	0	0	14.7

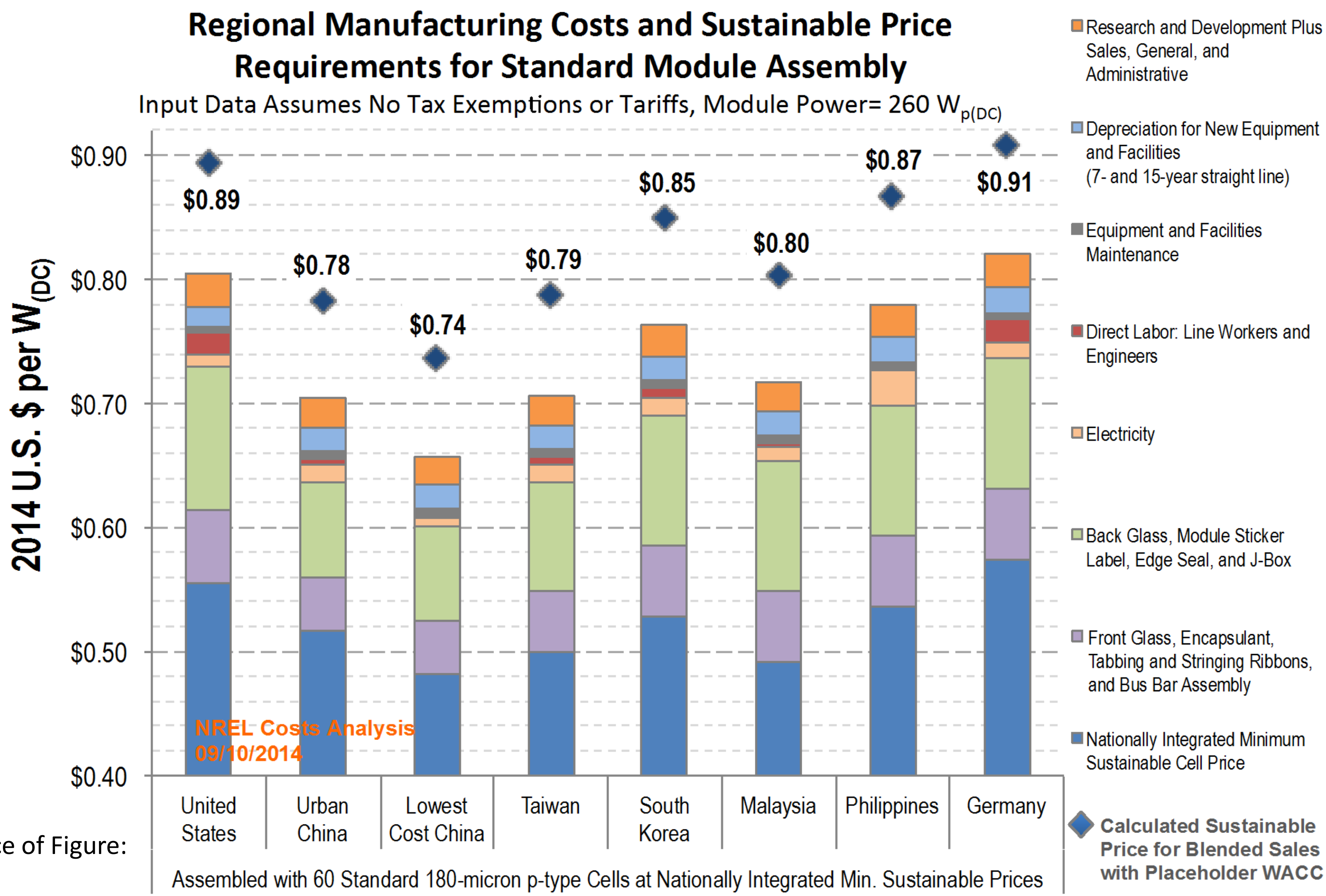
Source: IEA WEO 2013

- The PV industry is projected to grow at a CAGR of around 15% for the next 3 – 5 years. For any industry, this would be considered a fantastic rate of growth.
- Assuming a CAGR of 10% for the next 20 years, the IEA is projecting that PV will still be only 690 GW, only 7% of global electrical generating capacity under the IEA's New Policies Scenario.



Polysilicon
Cz ingot & wafering
Cells
Modules

Standard Module Assembly with Nationally-Integrated Minimum Sustainable Cell Prices



Source of Figure: NREL

Enabling Massive Scaleup of PV

TW PV scaling barriers that must be eliminated:

- Lack of low-cost energy storage
  > Not a pressing issue at small PV penetrations but quickly a barrier at modest penetrations.

  > Solutions we need won't be just electrochemical – need multiple approaches including conversion to fuels for seasonal storage.
- Capital intensity of the existing cSi supply chain

  Low margins across the supply chain create a significant barrier to raising the capital needed for new plants (polySi and wafering especially).

  ⇒ $1.2B and 2 years for 20,000 MT of polySi capacity, enough for 4GW.
- Present higher efficiency approaches are too costly
  > Need inexpensive solutions for adding a high quality, 1.7 - 1.9 eV top cell to a wafer based cSi cell.

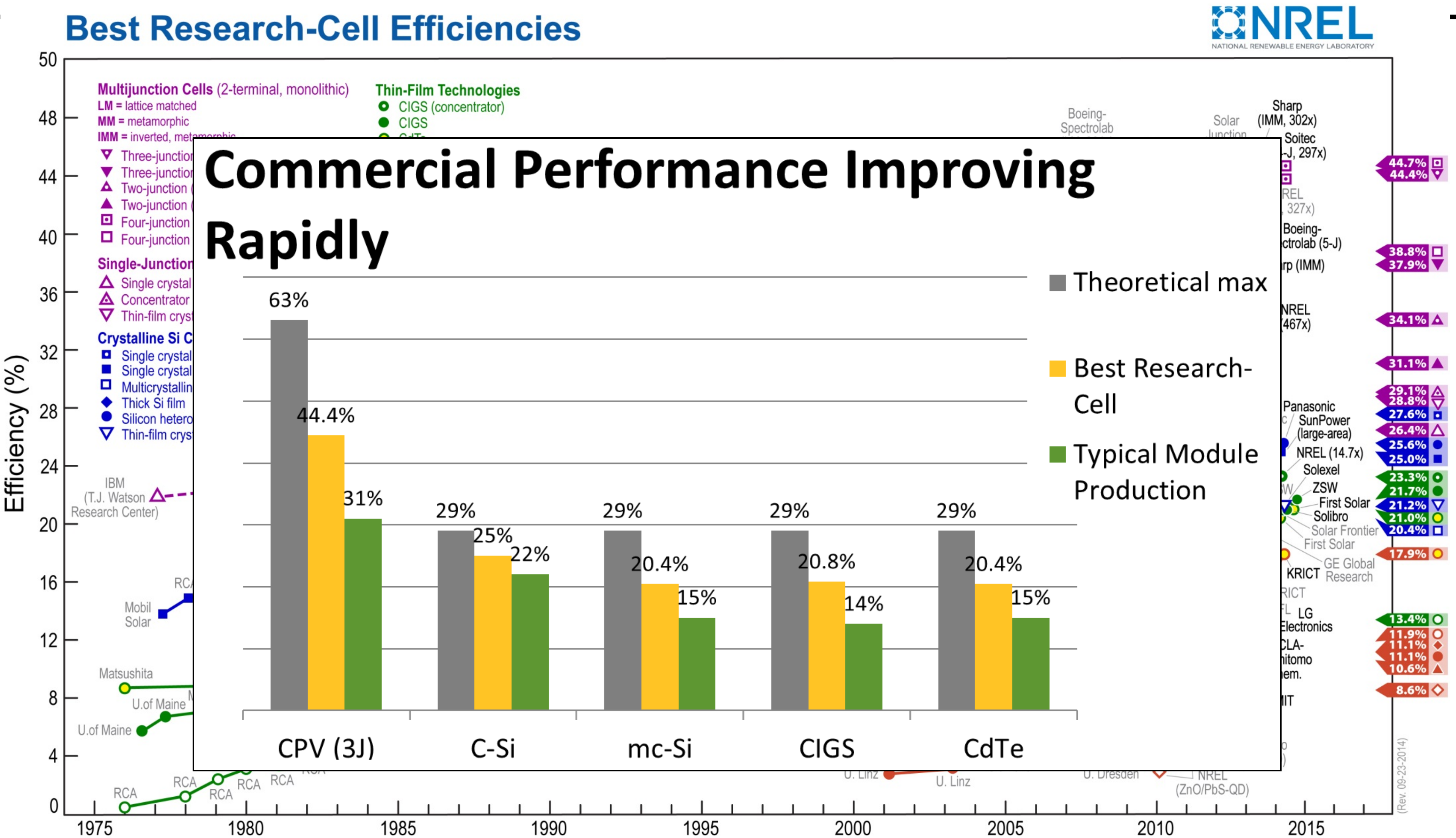
  > Holy grail is to lower cost enough to bring space cells to earth.

  ⇒ Need research leading to industrial solutions that will enable low cost 2-junction, 1-sun III-V cell manufacturing.

Enabling Massive Scaleup of PV (cont.)

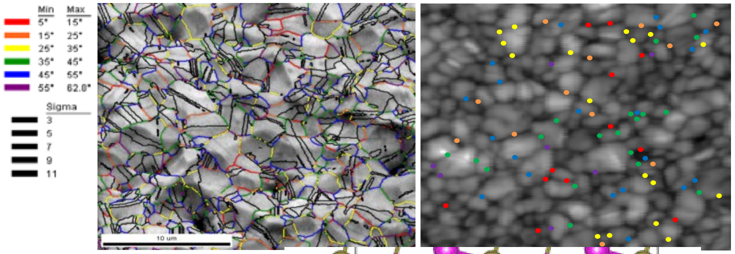
- Energy payback time is too long
  - > Most cSi panels today have EPTs approaching 2 years.
  - > For cSi, elimination of wafers cut from ingots remains an important goal but efficiency cannot be compromised.
- PV reliability and durability
  - > Panels today come with at least a 20 year warranty but many still degrade too fast or experience failures much too frequently.
  - > Service lives for PV panels need to be longer with lower degradation rates.

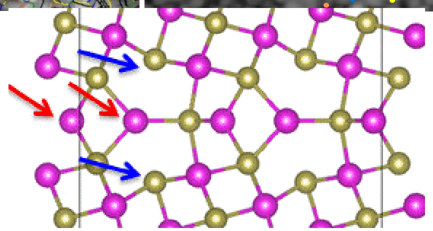
Commercial Performance Improving Rapidly

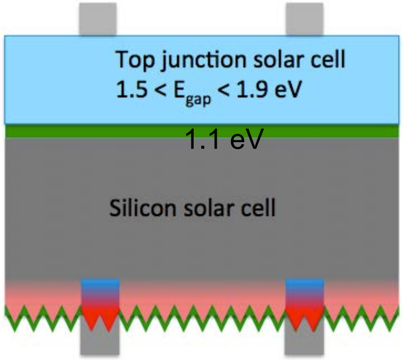


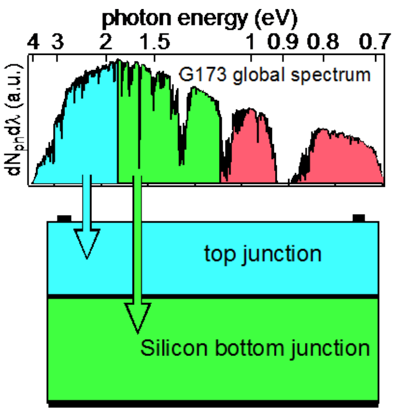
Important PV Research Fronts

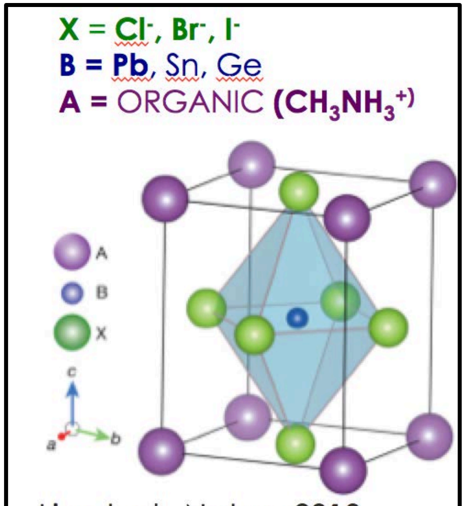
- High Efficiency Thin Films – Improved carrier lifetime and development of doping techniques will boost commercial module efficiency to 16%.
- Si Tandem Cells – Potential to increase the best cell efficiencies by 10%, to over 30%.
- Low Cost III-V 1J & 2J Cells – Potential to lower III-V growth cost by 1 – 2 orders of magnitude.
- "Kerfless Si" Wafers & Cells – Potential to cut supply chain capital investment by 50% with comparable cell performance.
- Perovskites – Very new polycrystalline thin film technology that has already demonstrated η > 17%.









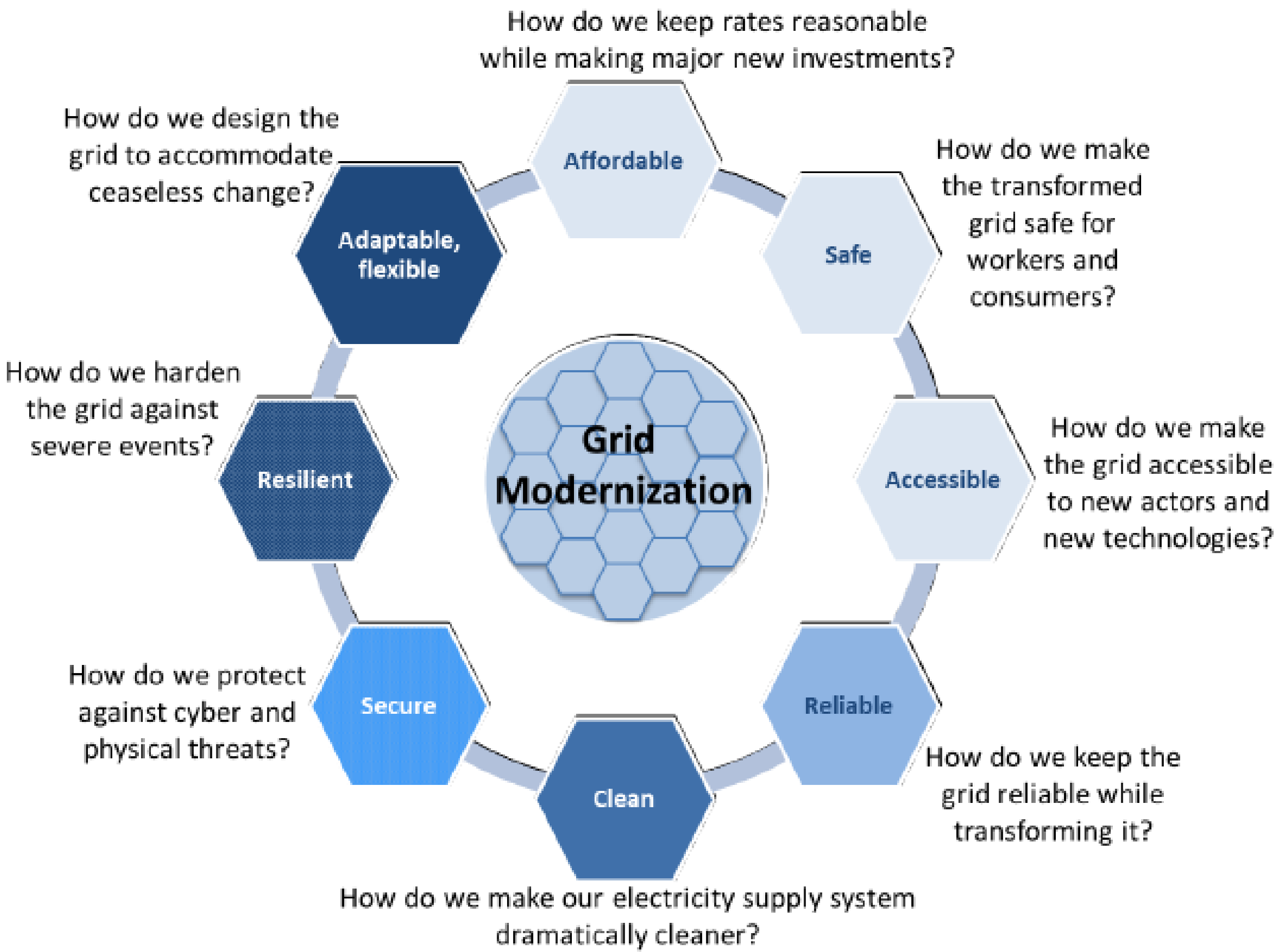


Liu et. al., Nature 2013

Why Grid Modernization?

The existing electrical grid has served us well…
but a clean energy future needs a modernized grid.

Key Attributes of a Modernized Grid



DOE Grid Modernization Initiative

System Control and Power Flow

Design and Planning Tools

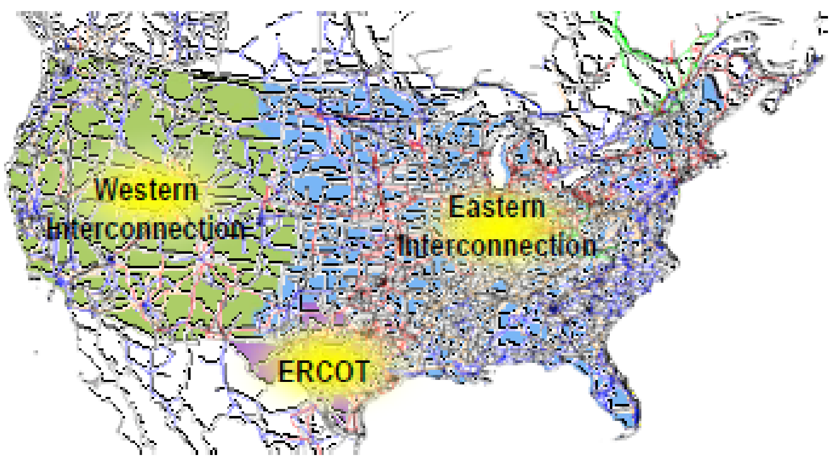
Sensing and Measurements

Devices and Integrated System Testing

Institutional Support

Security and Emergency Response

Regional Partnerships



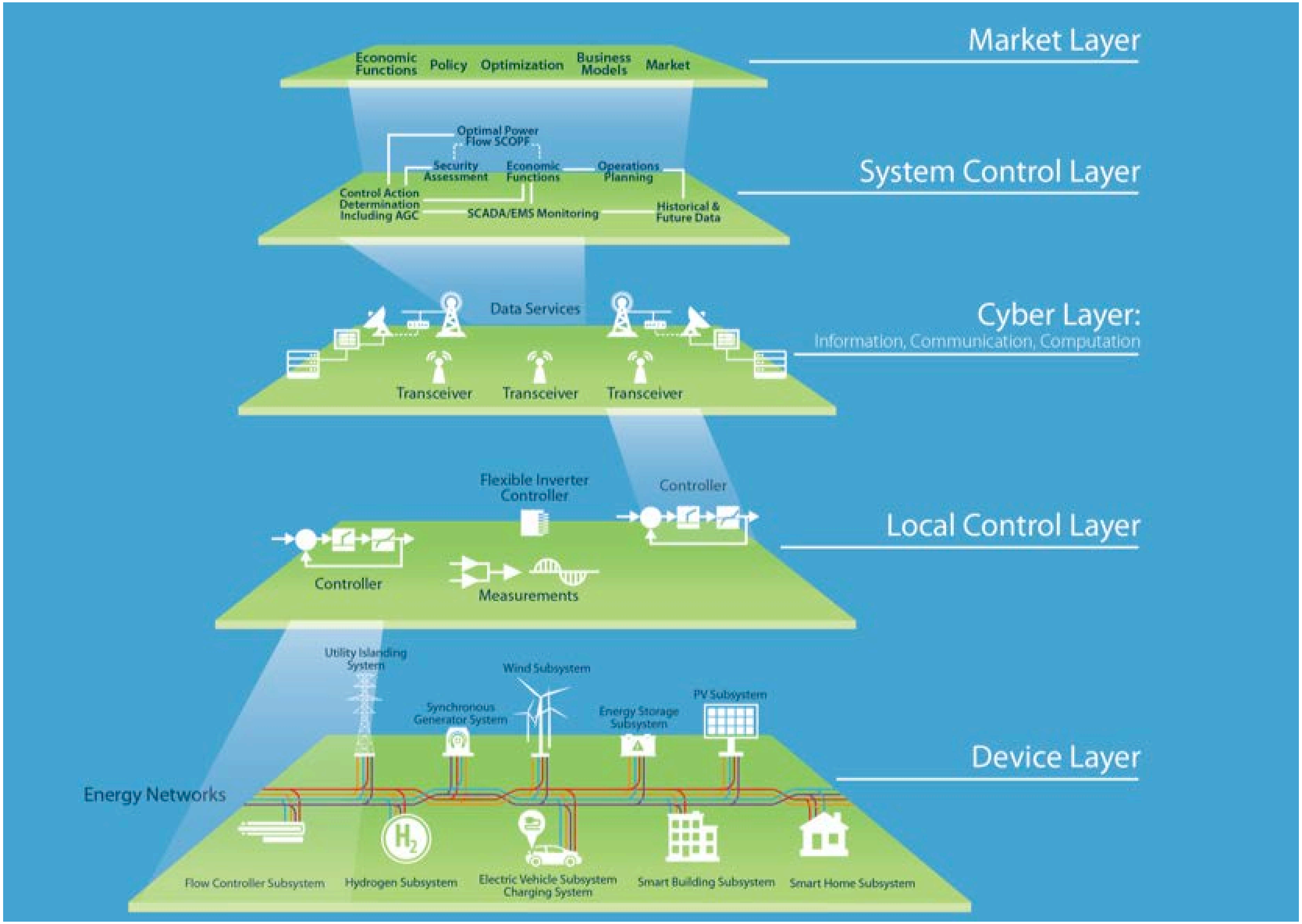
Challenges

- Aging infrastructure
- Increased asset stress
- Fuel mix changes
- Increase variability and uncertainty
- More information and potential control points

Goals

- Maintain reliability, safety, affordability
- Increase security and resilience
- Double installed renewables by 2020
- 80% clean electricity by 2035

Integrate Across Functional Layers



U.S. Department of Energy Emerging Grid Modernization Research Elements

Devices and Integrated Systems

– Device development, testing, validation, integration, and specifications

Grid Sensing and Measurement

– Transmission and distribution data analysis, visualization, sensors and communication

Design and Planning Tools

– Advanced computation for grid planning, integrate transmission and distribution planning tools

System Control and Power Flows

– Advanced computation for grid operations, control theory development, EMS and DMS and forecasting, whole grid control, power flow control

Grid Security and Resilience

– Accelerating situational awareness, cyber security monitoring and solutions, incident response, transformer testing, and specifications

Institutional Support

– Pricing, market design and business models, technical assistance to regions, international technical assistance

Energy Systems Integration Facility

Energy Systems Integration

Addressing the challenges of large-scale integration of clean energy technologies into the energy systems infrastructure
http://www.nrel.gov/eis/facilities_esif.html

"This new facility will allow for an even stronger partnership with manufacturers, utilities and researchers to help integrate more clean, renewable energy into a smarter, more reliable and more resilient power grid." *- Energy Secretary Ernest Moniz*

NREL NATIONAL RENEWABLE ENERGY LABORATORY | ENERGY SYSTEMS INTEGRATION FACILITY

U.S. DEPARTMENT OF ENERGY

- NREL's largest R&D facility (182,500 ft^2/20,000 m^2)
- Space for ~200 NREL staff and research partners
- Petascale HPC and Data Center supports all research at NREL
- Labs focus on R&D of integrated energy systems
  - Electricity
  - Fuels
  - Transportation
  - Buildings & Campus
- Integrated electrical, thermal, fuel, and data infrastructure

External Partnership Highlights

Energy Systems Integration

- Google
- Advanced Energy
- Toyota
- Wyle
- SolarCity and HECO
- San Diego Gas & Electric
- Southern California Gas
- CSIRO
- Duke and Alstom
- Solectria
- EPRI
- Houze
- American Vanadium
- SunPower
- Abengoa Energy
- Solar Power, Inc.
- Asetek

TECHNOLOGY ADDRESSED

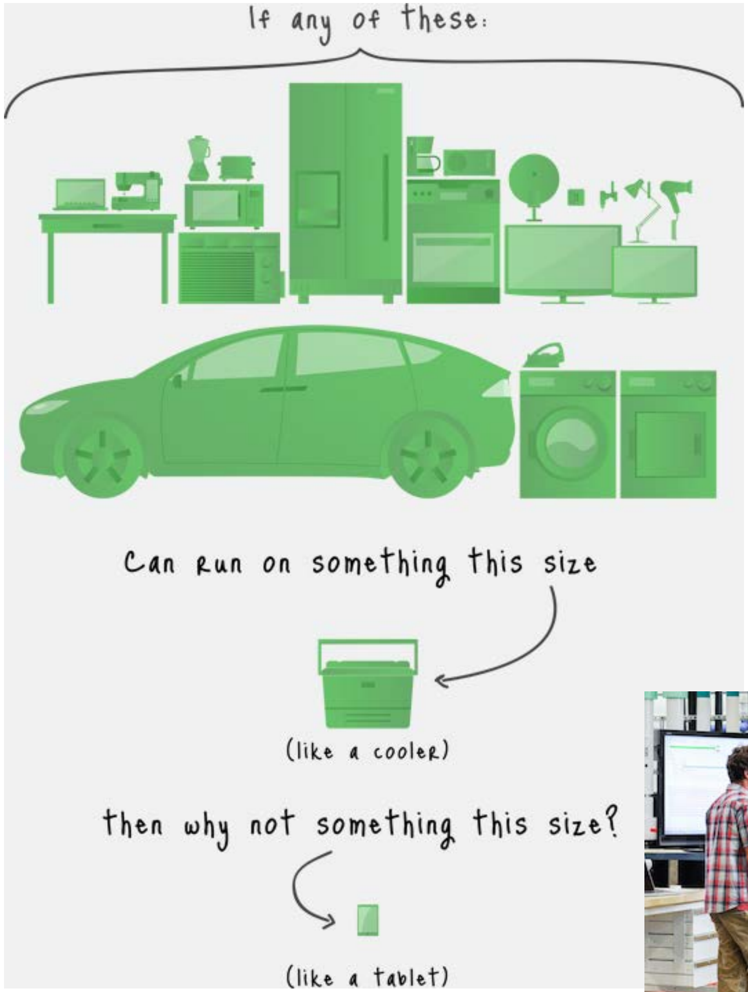
Build smaller power inverters for use in PV power systems. Wide band-gap semiconductors.

R&D STRATEGY

Under Google's "The Little Box Challenge", NREL researchers will evaluate each inverter's efficiency and performance during the same set of typical operating conditions spanning 100 hours.

IMPACT

Shrinking the current inverter and making it dramatically cheaper to produce and install would enable more PV-powered homes, more efficient distribution grids, and help bring electricity to remote areas.



NREL + Advanced Energy

Energy Systems Integration

TECHNOLOGY ADDRESSED

Solar inverter controls validation for high penetration utility and commercial photovoltaics (PV).

R&D STRATEGY

Demonstrate 500 kW and 1MW PV inverter performance by connecting the inverter to MW-scale grid simulators, PV simulators, load banks and real-time electric distribution feeder models.

IMPACT

Facilitate the increase in PV saturation without negatively impacting the distribution grid toward CA goals of 33% RE penetration by 2030.

NREL + Wyle

Energy Systems Integration

TECHNOLOGY ADDRESSED

DoD Army forward operating base power management using the Consolidated utility base energy (CUBE) system

R&D STRATEGY

Develop and test prototype integrated mobile power system that optimized fuel use by incorporating PV, wind, and storage. The system is capable of smoothly transitioning between operation as a stand-alone unit and connected to a utility grid.

IMPACT

Significantly reduce fuel use and extend mission critical operations up to 48 hours ultimately saving soldiers lives.

NREL + SolarCity and HECO

Energy Systems Integration

TECHNOLOGY ADDRESSED

Interconnection challenges when connecting distributed PV into the electrical distribution grid such as in Hawaii (HECO).

R&D STRATEGY

Inverters from various manufacturers will be tested at ESIF using NREL's unique power hardware-in-the-loop capability to evaluate system-level issues such as anti-islanding and volt-VAR support.

Union Bridge, MD

IMPACT

Hawaii is moving towards 50% renewable energy and this project will work to improve the safety, reliability and stability of the electric power systems that include high levels of distributed PV.

NREL + Southern California Gas

Energy Systems Integration

TECHNOLOGY ADDRESSED

Use of gaseous energy storage (hydrogen) to enhance the value of solar or wind resources (Power-to-Gas)

R&D STRATEGY

Develop a power-to-gas storage dynamic simulation model incorporating specific performance parameters. Build and operate a small-scale physical power-to-gas system using equipment and other resources available at ESIF to test the system.

IMPACT

Potentially disruptive solution to storing excess solar and/or wind energy by utilizing the existing natural gas infrastructure

NREL + San Diego Gas & Electric

TECHNOLOGY ADDRESSED

Utilization of high penetration PV and energy storage in islanded microgrids.

R&D STRATEGY

Develop a real microgrid scenario with high penetrations of PV (Borrego Springs, CA) that will be tested in the ESIF, and investigate multiple control cases for firming PV using storage in microgrid scenario.

IMPACT

Scale up of local microgrid controller to larger utility power system. Enable effective utilization of high penetration PV in islanded microgrids using proper energy storage sizing and placement. Increase local customer reliability during natural disasters

NREL + CSIRO (Australian National Lab)

Energy Systems Integration

TECHNOLOGY ADDRESSED

Advance microgrid technology components and optimize their use for remote applications in Australia, primarily PV.

R&D STRATEGY

Perform prototype testing of the microgrid controller in the ESIF to test the hardware's ability to manage the output power of a diesel generator in the presence of loads and solar PV. Demonstration of co-simulation between CSIRO and ESIF that allows virtual connection of test equipment.

IMPACT

Simplify the integration, accelerate the deployment, and lower the cost of hybrid distributed generation systems by 20% by creating 'plug and play' solar technology for these applications. First demonstration of co-simulation with hardware and control signals across Pacific.

Innovation, Integration and Adoption

Reducing Investment Risk

- Enable basic and applied clean energy technology innovation
- Accelerate technology market introduction and adoption
- Integrate technology at scale
- Encourage collaboration in unique research and testing "partnering" facilities

Mobilizing Capital

To achieve a clean energy vision, we must…

Invest in innovation

Invent the future we desire

Improve access to capital

Partner on a global scale